Figure 1. Geometric limits for relating satellite e.i.r.p. to
mobile earth station e.i.r.p

3. **Analysis**

The satellite e.i.r.p. density value that is equivalent to
an Earth-based e.i.r.p. density value can be determined from the
difference (in dB) between free space losses on the path between
the receiving satellite and the Earth (i.e., the path that
pertains to the mobile earth station e.i.r.p. density) and the
direct path between satellites, as in equation (1d). Because the
direct path may be shorter than the path between the receiving
satellite and Earth, the satellite e.i.r.p. density in certain
directions will have to be less than the Earth-based equivalent
single entry e.i.r.p. density

$$E_{max}(\phi) < E' - \{32.45 + 20 \log [f] + 20 \log [R_{des}]\} +$$

$$\{32.45 + 20 \log [f] + 20 \log [R_{int}(\phi)]\} \qquad (1c)$$

$$E_{max}(\phi) < E' - 20 \log [R_{des}/R_{int}(\phi)] \qquad (1d)$$

where:

$E_{max}(\phi)$:   maximum permissible satellite e.i.r.p. density
(dBW/4 kHz) at an off-nadir angle ϕ;

ϕ: off-nadir angle measured at the transmitting satellite
(degrees);

f: frequency (MHz);

R_{des}:   path length (km) between the receiving satellite and
Earth;

$R_{int}(\phi)$:   path length (km) between the transmitting satellite and
the receiving satellite in the direction of the off-
nadir angle ϕ.

3

The following equation is used to compute the actual off-nadir e.i.r.p. density produced by a transmitting satellite:

$$E(\phi) = E_t - D(\phi) - 10 \log (B/B_{ref}) \qquad (1e)$$

where

$E(\phi)$: calculated e.i.r.p. density (dBW/4 kHz) generated by the interfering satellite;

$D(\phi)$: discrimination of interfering satellite antenna (dBi) in direction of the receiving satellite;

E_t: total peak e.i.r.p. of interfering satellite.

Different satellite transmitting antenna beams may exhibit different values for $D(\phi)$ and E_t in the same direction ϕ; thus, the total power of all beams should be considered. In order to ensure that no harmful interference is caused by secondary MSS space-to-Earth transmissions to primary Earth-to-space transmissions in the band, it is necessary that:

$$E(\phi) < E_{max}(\phi) \qquad (1f)$$

3.1   E.I.R.P. density in the direction of an Earth tangent

For the near-antipodal situation illustrated in Figure 2, R1 and R2 are measured along an Earth tangent and R_{int} (distance between transmitting and receiving satellites) is equal to the sum of R1 and R2 (R2 is the distance between the transmitting satellite and Earth along an Earth tangent). Thus, the satellite e.i.r.p. in the direction of the Earth tangent should be restrained as shown in equation (2).
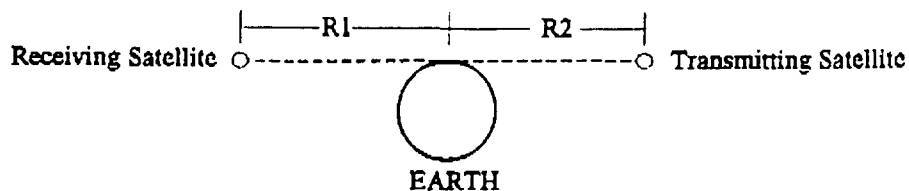
Receiving Satellite O------------------------------O Transmitting Satellite
|———R1———|——— R2 ——|

EARTH

Figure 2.   Geometry for "nearly antipodal" interference interactions

$$E_{max}(\phi) < E' - 20 \log (R1/(R1 + R2)) \qquad (2)$$

3.2 E.I.R.P. density in the satellite backlobe direction

Figure 3 illustrates the geometry for the case where interference may occur from transmitting satellite backlobe emissions. For a receiving satellite at a higher altitude than the LEO transmitting satellite, satellite e.i.r.p. density in the direction opposite nadir should be constrained as shown in equation (3).
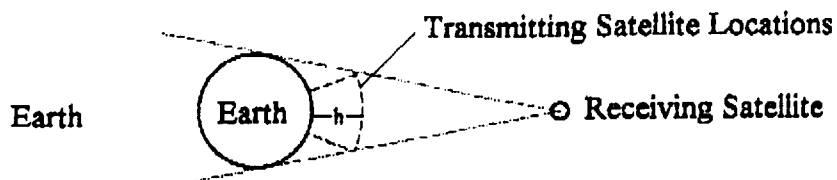

Figure 3. Geometry for interference interactions involving transmitting satellite backlobes.

$$E_{max}(180) < E' - 20 \log [h_{des}/(h_{des} - h_{int})] \qquad (3)$$

where h_{int} is the altitude of the transmitting satellite in km and h_{des} is the altitude of the receiving satellite in km.

3.3 E.I.R.P. in other directions

As the angle ϕ is decreased from 180° (i.e., the direction opposite nadir), the value of $R_{int}(\phi)$ increases from the minimum value used in equation 3 and the e.i.r.p. density value determined in Section 3.2 can be increased. Further study is needed to determine the manner in which the e.i.r.p. values might be interpolated from the values in Sections 3.1 and 3.2 for angles ϕ between 180° and the angle toward the Earth tangent.

4. Summary

A preliminary model is presented to determine maximum permissible e.i.r.p. density levels that may be produced by secondary MSS space-to-Earth transmissions operating in the same band as primary MSS Earth-to-space transmissions. This model relates the permissible downlink interfering e.i.r.p. density to the uplink e.i.r.p. density that may be permitted under sharing arrangements for primary uplink transmissions.

Further study is needed for cases where the receiving satellite is located between Earth and the transmitting satellite, particularly with regard to the backlobe

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characteristics of receiving satellite antennas and requirements for protecting receivers located on Earth and operating in other services. Further study is also needed of the potential for interference via Earth backscatter of the downlink signals and interactions between transmitting and receiving geostationary satellites. In addition, the following factors should be considered in further work on this topic: (1) the total interference environment (including Glonass radionavigation satellite signals) and the satellite receivers' ability to cope with the aggregate interference; (2) receiving satellite antenna gain in the direction of the interferers; (3) the modulation, bandwidth, and power of the desired and interfering signals; (4) the potential effect of voice activation; (5) the applicable sharing criteria; (6) the impact of uplink power control; and (7) the distribution of transmitting earth stations and the associated receiving satellite antenna gain.

C

MAXIMIZING THE USE OF THE MSS
WARC '92 ALLOCATIONS

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ABSTRACT:

There are several proposals for MSS systems to utilize the 1.6 and 2.5 GHz bands. Within the USA there are six proposals, outside the United States INMARSAT and others have filed IFRB advanced notices of intent to bring into service global MSS systems using these bands. The potential MSS providers need to consider how their systems will impact the other users both current and future of these bands, in particular, Radio Astronomy, GLONASS and the fixed microwave systems, as well as coordinate among themselves. The MSS systems should meet the limits established by WARC '92 for the usage of the band. Additionally, interference to primary uplinks from secondary downlinks emanating from satellites operating in a bi-directional manner must be eliminated as well as interference from these secondary emissions into other band users such as GLONASS or future radio navigation aids.

Two methods for band sharing by MSS operators have been put forward, full band sharing and band segmentation. While band segmentation is an easy solution it would result in an inefficient use of the spectrum. On the other hand, CDMA is the appropriate technology for high capacity and multiple system provider services. CDMA has been shown to allow multiple system providers to more effectively share frequencies by multiple system bandwidth sharing within a service area. CDMA systems retain a significant portion of the non-sharing capacity even when faced with a single similar competing system. Finally, CDMA's low power spectral density reduces interference into other non-MSS systems which share the bands.

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SHARING ISSUES IN THE 1610-1626.5 AND 2483.5-2500 MHz BANDS

There are two issues for the potential Mobile Satellite Service (MSS) operators to contend with in regard to sharing the frequency bands allocated by WARC '92 for MSS in the 1.6 and 2.5 GHz band segments. The current and future non-MSS users of the band must be protected from unwanted interference and loss of function or capacity. The second issue is how the various domestic and international operations by potential MSS providers can share the spectrum and maximize the utilization of this scarce resource.

Current and Future Users of the MSS Bands

The current users of the 1.6 MHz band fall into five categories;
(1) Radio Astronomers which are providing extra-terrestrial emission passive research;
(2) Fixed services both on a secondary and a primary basis;
(3) Swedish Radars;
(4) Radio Determination Satellite Service; and
(5) Radio Navigation Aids such as GLONASS.

The users of the 2.5 MHz band fall into two categories;
(1) Fixed services; and
(2) Radio Determination Satellite Services.

Potential MSS Systems

There are several proposals for MSS systems to utilize the 1.6 and 2.5 GHz bands. Within the USA there are six proposals, outside the United States INMARSAT and others have filed IFRB advanced notices of intent to bring into service global MSS systems using these bands. The six US applications fall into two categories; those using CDMA and those using TDMA or FDMA. One of these systems plans to use the 1.6 GHz band in a bi-directional fashion adding another dimension to the discussion of band sharing with existing services.

The potential MSS providers need to consider how their systems will impact the other service current and future users of these bands, in particular, Radio Astronomy, GLONASS and the fixed microwave systems. All aspects of potential interference including WARC'92 limitations, out of band emissions, and system to system interference should be carefully investigated.

SHARING METHODS WITH CURRENT AND FUTURE USERS

There are two basic methods of MSS providers sharing with other service users both existing and future. First, the MSS systems should meet the limits established by WARC '92 for the usage of the band. For MSS operators this means limiting emissions from user equipment and satellites such that EIRP density limits in the 1.6 GHz band and Power Flux Density (PFD) limits in the 2.5 GHz band are maintained. Additionally, interference to primary uplinks from secondary downlinks emanating from satellites operating in a bi-directional manner must be eliminated as well as interference from these secondary emissions into other band users such as GLONASS or future radio navigation aids.

However, according to international regulation, coordination is permitted if

required. For global systems such as these proposals it may be difficult to accomplish this coordination on a piecemeal basis. Thus, the recommended approach is to meet the requirements of WARC '92 and establish world wide an EIRP density on the 1.6 GHz uplink across the entire 16.5 MHz band that meets the lower of the WARC '92 limits of -15 dBW/4 KHz. This will ensure that in the future, aeronautical radio navigation aids such as GLONASS will be able to use all of their allocation without being required to perform complex coordination processes. Furthermore, adherence to this standard will enable further band sharing among the proposed MSS users, enhancing and maximizing the utilization of the band.

METHODS AVAILABLE FOR SHARING BETWEEN MSS SYSTEMS

Full band sharing and band segmentation are the two methods for sharing between various MSS system providers. Full band sharing is discussed below under the title of Maximum Usage Considerations. Band segmentation would result in inefficient use of the spectrum and is inconsistent with the United States' position at WARC '92 where it emphasized that it sought an allocation for a service not a system. By band splitting to accommodate a single TDMA or FDMA system, a defacto-monopoly may be given. The inefficiency comes from the fact if the band were split between two modulation techniques, such as CDMA and TDMA, the TDMA portion is not available for spectrum efficient band sharing by multiple providers as allowed by CDMA techniques. In addition, with band splitting there is additional waste, since there is no way for a more heavily loaded CDMA system to gain additional channels while a potentially lightly loaded TDMA

competitor wastes its allocation. This is not the case with full band CDMA sharing.

MAXIMUM USAGE CONSIDERATIONS

CDMA is the appropriate technology for high capacity and multiple system provider services. CDMA has been shown to allow multiple system providers to more effectively share frequencies by multiple system bandwidth sharing within a service area. CDMA systems retain a significant portion of the non-sharing capacity even when faced with a single similar competing system. This means that the aggregate capacity of two systems is greater than 100% of the capacity of one system.

TDMA or FDMA, on the other hand, is inherently incapable of producing any capacity gain from the operation on more than one system. This occurs because the TDMA approach is fundamentally bandwidth limited. There are only so many channels and slots available in a given service area. Providing another satellite with co-coverage can only be useful if there is more capacity provided by the presence of an additional system. In fact, less capacity results when there are multiple systems using TDMA. In addition, with competing TDMA systems (with equal division of available channels) has additional waste, since there is no way for a more heavily loaded system to gain additional channels while the lightly loaded system wastes its allocation. This is not the case with CDMA sharing.

The best approach with CDMA is to overlay the CDMA systems in the same frequency band with no fixed or predetermined divisions of channel resources. Each operator can load its

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system until the system runs out of link margin. This means that the operator that provides the best service or lower rates or whatever consumers prefer will be able to use more than an allocated portion of the available spectrum. In short, systems utilizing CDMA maximize the use of the spectrum and efficiently adjust on a dynamic basis to serve the public.

CDMA is the most spectrum efficient sharing method because;

(1)   The way to efficient use of the spectrum is through spectrum reuse;
(2)   All efficient spectrum reuse schemes end up being interference limited;
(3)   When the system is interference limited CDMA is the best multiple access technique.

In a well designed, wide area communications system employing spectrum reuse, most of the interference comes from other homogeneous system users. With CDMA, capacity sharing boils down to power sharing, and therefore interference from non-homogeneous sources consumes a small portion of the CDMA system's capacity. The capacity lost to this interference source is determined by limitations placed on the CDMA system's power density as a result of coordination efforts. If the non-homogeneous interference sources are as efficient in their own use of power as the CDMA system, then a fair division of capacity resources can be made. If other systems are homogeneous, the utilization of spectrum resources is even more efficient. By being homogeneous, all systems would be designed to the same principles (CDMA signalling, power control, etc) and no user/system would use more power than required. Thus, for maximum

utilization of the scarce resources of the MSS bands homo- geneous CDMA systems should be adopted, systems such as TDMA or FDMA should be rejected.

Interference to other systems from a CDMA system will also be minimized on a per-user basis for several reasons;

(1)   Power control, inherent in CDMA, minimizes need for margins in the system link budget, power is only applied on a link by link basis and only when required.
(2)   The fact that the spectrum spread means that low rate convolutional codes can be used to lower the Eb/No requirement and therefore the transmitted power.
(3)   Voice activity gating eliminates interference from transmitters when voice users are not talking.
(4)   CDMA allows universal frequency reuse so that all beams can use all frequencies rather than being forced into some type of plan (ie 1/7) such as TDMA.
(5)   Wide-band signal spectrum produces a noise-like interference characteristic in other systems unlike TDMA which produces un-noise like transmit burst pulses.
(6)   When a CDMA system is operating at less than full capacity, interference to other systems will be reduced proportionally. This feature contrasts with TDMA systems which continue to produce full power transmit bursts even when only one user is talking.

A properly designed CDMA system is most benign in its interference to other types of systems that may be sharing the same spectrum and still provides the most efficient use of the spectrum when fully operating.

4

D

A Perspective on the Evolution of Multiple Access Satellite Communication

Andrew J. Viterbi, *Fellow, IEEE*

Abstract—The evolution of communication satellites is reviewed, with an emphasis on multiple access by large populations of users employing mobile and personal terminals. It is argued that the basic problem of mutual interference rejection is most effectively solved by employing modern digital technology to implement spread-spectrum modulation systems based on military antijam communication systems which are inherently robust to interference. A perspective on the impact of this approach on future networks of low earth-orbit satellites is presented, along with concluding remarks on the well-established theoretical foundations of the presently emerging satellite technologies.

I. INTRODUCTION

SATELLITE communication as a commercial enterprise is just over twenty-five years old. It is difficult to exaggerate its impact on our lives through making us real-time participants in major events occurring anywhere in the world [1] and by providing affordable wideband data services to large and diverse segments of the business world. Yet this technology is just approaching the "knee of the curve" of its ultimate utilization. The great fear of the early eighties that fiber optic networks would soon relegate communication satellites to the "dustbin of technological history" has dissipated.

Wireless and mobile personal communications have, in fact, become the buzzwords for the nineties. Admittedly, this enthusiasm has been generated more by terrestrial applications, specifically through the almost explosive demand for cellular telephone service in all industrially developed countries. This, however, has also inspired a reexamination of the role of satellites in providing universal and ubiquitous personal communication service even in remote and underdeveloped areas.

To focus on the actual utilization of satellites and the enabling technology which has evolved over the last third of this century and project this forward toward the first third of the next, we must begin by recognizing the three-way partitioning of the growth segments of the satellite communication industry:

1) *DBS:* primarily broadcast services, mostly direct video but with emerging direct audio as well, with little or no reverse link requirements

2) *VSAT:* private fixed networks of small earth termi-

nals, providing wideband data as well as conferencing, both voice and video services primarily to businesses

3) *Personal and Mobile:* public multiple access from and to a large consumer base.

We have purposely excluded large trunking applications, which initially were the predominant justification for satellites and which will continue but whose slow growth will soon relegate them to secondary status.

We shall concentrate mostly on the third area, for here the technology is most rapidly evolving and the impact of new development is greatest. In all three, it is evident that digital technology is rapidly overtaking analog transmission. The predominant reason is the diminishing cost of digital processing technology, following the VLSI performance curves of component density and processing speeds doubling every two years. Additionally, in DBS, the cost advantage in sharing one transponder for multiple programs (as many as ten simultaneous NTSC transmissions on a single 24 MHz transponder) is the immediate driving force, much more than the increasing practicality of digital HDTV transmission. We believe that VSAT's, though presently the fastest growing segment, will lose ground relative to the other two segments simply because of the more restricted market (industrial rather than consumer) and to a lesser extent possibly from competition with wireline broadband services. At the same time, however, by sharing the technology with the wider personal applications, it will benefit from the latter's economies of scale and may consequently hold its own in the competition with terrestrial services.

Far more than for VSAT applications, the evolution of personal and mobile communications, terrestrial as well as satellite, will be affected by the choice of a multiple access technique. Curiously enough, terrestrial wireless communication which predates satellites by two-thirds of a century is following rather than leading both in the transition to digital transmission and in the migration to optimal multiple access technologies. Even more surprisingly, the same approach seems to be right for both.

A. Digital Technology Dissemination

To explore this, let us first digress into a review of digital transmission technology for communication satellites and its influence on terrestrial wireless communication; then we shall return to trace the same trends for multiple access techniques. Early digital modulation systems date

back to the middle-to-late sixties. NASA was in the vanguard, with DoD a close second. By the mid-seventies, most government satellite systems had standardized on QPSK modulation, or some variant thereof, with forward error correction employing convolutional codes. Of course, these were mainly point-to-point systems. After some delay, INTELSAT followed with digital systems for telephone trunking applications, resulting in networks with a moderate number of earth stations. INMARSAT shortly thereafter began the first mobile digital service. Regional networks such as EUTELSAT also implemented primarily digital service, for all but TV broadcast usage.

In contrast, the first terrestrial wireless digital service is just beginning, with the gradual migration of cellular telephony over the rest of this decade from analog to digital technology. Perhaps not surprisingly, therefore, most proposed systems (the European GSM, the North American D-AMPS, and the Japanese variant on the latter) employ almost exactly the same transmission technology as that prevalent in digital satellite communication[1].

The reasons for this slow acceptance of digital technology by the terrestrial wireless industry are several. First, there was the inertia inherent in a massive established base of FM two-way radio. Second, most current services were conceived in the sixties and early seventies, long before solid-state integrated circuits had reached the levels of economy and performance which could make low-cost digital subscriber units possible. Third, an early perception of the communication engineering community was that the more sophisticated digital transmission techniques improved efficiency only for power-limited applications, but not for bandlimited systems. This view was shared by most satellite communication system designers of that period. It was only recently that the evolution of digital source coding (both voice and video), coupled with a better understanding of digital modulation techniques with embedded forward error correction, has made it apparent that digital techniques have as much or more to offer bandlimited applications, throughout the wireless industry and even for many conventional wireline systems as well.

B. Military Satellite Role Models

Now let us return to our main theme, that of multiple access networks for very large numbers of users. Satellites by their very nature represent the ideal multiple access medium, especially geosynchronous satellites which are accessible to all who can afford the antenna and transceiver to close the link budget. Consequently, the first serious study of multiple access wireless networks emerged from the (military) satellite community in the mid-sixties [2]. Among other important contributions, this paper first defined frequency-, time-, and code-division[2]

multiple access (FDMA, TDMA, and CDMA). Unfortunately for the future of the wireless industry, communication satellite engineers focused primarily on two considerations, neither of which is currently a central issue: nonlinear transponder characteristics and service for a few users, employing mostly large earth terminals. These concerns seem to lead to a choice of TDMA over the other two. Yet, carrying the TDMA approach to its extreme imposes a common format on users of all terminal sizes and requirements. This, of course, is closely related to the development of on-board processing, on which more will be said.

At the same time, multiple access satellite technology was driven in new directions by military satellite requirements. The overriding consideration here is interference, not transponder characteristics.[3] Interference is pervasive, unavoidable, and uncontrollable especially in the geosynchronous satellite, which is a "sitting duck" for any hostile intentional interferer. Military communication has faced the need of foiling jammers ever since its inception in World War I. Yet, only recently has antijam communication technology been greatly improved for the protection of the very precious and powerful, but simultaneously vulnerable, communication resources provided by the geosynchronous satellite. These improvements have been made possible, of course, by the phenomenal advances in signal processing techniques through solid-state VLSI circuits.

Interference in all wireless communication can be suppressed quite successfully by a combination of two techniques: spread-spectrum modulation and multiple-element antenna arrays. For satellites, the former is the more important since it is more generally applicable and more robust, while the effectiveness of the latter depends on relative user and jammer geometries. Reduced to simplest terms, spread-spectrum antijam techniques involve the use of a wideband carrier, which appears random to the intentional interferer but which is known or can be reconstructed by the intended receiver. This "pseudorandom" carrier can be demodulated by the receiver with only little more complexity than what is required for a conventional narrowband carrier. At the same time, the pseudorandom carrier demodulation process widens the hostile interference signal and makes it appear like the wideband (white) noise of thermal origin, which is the inescapable limiting factor for satellite links. Actually, there are two basic forms of spread-spectrum communication: direct sequence and frequency hopping. In a strict sense, the above description holds only for the former, but with some freedom of interpretation and some precautions, it pertains to the latter as well. The degree of resistance to hostile interference, generally called the *jamming margin*, grows directly with the bandwidth over which the signal is spread. For large spreading bandwidth (more than 100 MHz), frequency hopping is more practical than direct

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[1]The one innovative exception here has been the use of a low-rate vocoder, since bandwidth efficiency is the dominant concern.

[2]In this paper, code division was called spread spectrum (SSMA); the complete terminology is direct-sequence spread-spectrum CDMA.

[3]Nonlinearities can often aggravate the effect of interference however, unless appropriate precautions are taken through signal design.

sequence; however, even in such cases, a hybrid of direct sequence and frequency hopping provides the greatest immunity.

In military satellites, spread spectrum offers a multitude of advantages [3], often simultaneously: protection from intentional interference, security and privacy, low detectability of the transmitter's signal and hence its position, position location of friendly users, and, if a large jammer is not present simultaneously, multiple access for large populations of users as we shall presently discuss.

C. Implications for Commercial Satellite Multiple Access

The reader may question the relevance of the above to the growth areas in commercial satellites which we addressed earlier. The answer is that with multiple access of one or more satellites by a large population of users, some interference is unavoidable even with a high degree of coordination among users and satellites. The nature or source of this interference falls into one or more of three categories.

a) *Spatial overlap*—neighboring satellites with small arc separation interfering with, or receiving interference from, small user terminals with relatively large antenna beamwidths

b) *Spectral overlap*—diverse users in adjacent frequency bands with spectral spillover due to inadequate filtering or to cross-products of nonlinear amplifier origin; possibly also the consequence of polarization overlaps

c) *Temporal overlap*—intersymbol interference caused by mismatched filters and by multipath effects.

The conventional means for attenuating these effects include, respectively, spatial guardbands for antennas, frequency guardbands for filters and amplifier backoff, and equalization and time guardbands. As these effects apply to FDMA, for example, they require that sufficient frequency guardbands be provided between carriers and, for mobile users, doppler shifts impose ever wider guardbands, the higher the frequency band of transmission. For TDMA, time guardbands are required to accommodate different user propagation delays[4], as well as additional multipath delay. The overhead associated with guardbands grows monotonically with the number of users involved. The most common and effective means, however, which applies to all categories is to provide margins in the link budget to account for these deteriorating factors. These margins often range from 3 dB to 6 dB and represent a system capacity reduction. An equally serious issue, also reducing efficiency, is the means for providing access to a large population of infrequent users. While many protocols for demand assignment have been em-

ployed and improved on over the years, efficiency of utilization of the satellite resources, particularly for packet switched systems, is limited by the delay in reallocating resources.

The alternative to guardbands and margins, and even to demand assignment overhead, is to use a spread-spectrum signal for all users and to share the frequency allocation. Known more commonly in civilian applications as code division multiple access (CDMA), this makes every user's signal appear as wideband noise to every other user's receiver, and this includes signals from spatially overlapping satellites as well. Wideband noise, however, is the natural environment of a satellite receiver, and the same signal processing receiver technology that works well in power-limited applications will work equally well in a heavily user-loaded system, thereby providing bandwidth efficiency as well. To complete the analogy, the large jammer in military communications is replaced by many small interferers; thus, the military "jamming margin" is replaced by other user-to-desired user ratio which, for equal powers, equals the number of users supportable. This requirement of equal user power is achieved by implementing power control, which in turn provides a number of ancillary benefits.

The first commercial satellite service to use this approach was implemented by Equatorial Communication Corporation, later acquired by CONTEL, which in turn became part of GTE. A more far-reaching application was the first Ku-band mobile satellite service, providing messaging and position reporting through the OmniTRACS® system developed and operated by Qualcomm, Inc. Aimed primarily at transportation companies, it currently supports two-way communication with over 25 000 vehicles not only in North America, but in Europe, Latin America, and Japan as well. Both these applications are more power-limited than bandwidth-limited. Bandwidth efficiency can also be gained. By avoiding the spatial antenna guardbands in a multiple antenna system and utilizing both vertical and horizontal polarizations, which in conventional systems is precluded by cross-polarization interference and automatically (instantaneously) reassigning channels during quiet periods of voice conversations, a properly designed CDMA system has been shown to provide about 2.5 times as many conversations [4] in the same bandwidth as an FDMA or TDMA system [5]. These improvements turn out to be modest compared with what is possible in terrestrial cellular systems, where much larger spatial guardbands (in the form of frequency reuse requirements for conventional cellular systems) are avoided by CDMA, resulting in more than a ten-fold capacity increase [6].

D. Future Satellite Networks

Future systems promise to be far more ambitious in terms of the number and category of user terminals. From the present tens of thousands of business-related terminals, there will be growth to millions of consumer sub-

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[4]The geosynchronous satellite presents the most benign environment for TDMA because geometries are reasonably constant even with mobile users. For terrestrial and, even more, low earth orbit (LEO) satellites, the situation is much worse.

scribers, as mobile and personal service may be provided by satellites, as an extension of cellular-type service outside metropolitan areas as well as for underdeveloped countries. The most elaborate proposal of this nature has been Motorola's IRIDIUM® project which envisions a network of 77 low earth orbit (LEO) satellites, tightly synchronized in time, with on-board signal processing and multiple cross links, intended to connect any two mobile terminals practically everywhere on earth without the need for any existing terrestrial facilities.

In sharp contrast with this network of highly controlled, time synchronized, and cross-linked satellites, several other LEO satellite network proponents intend to employ CDMA techniques without coordination among satellites. The Loral/Qualcomm Satellite Services proposal for the GLOBALSTAR® system envisions an approach which is a direct and natural extension of cellular service. Using the same CDMA waveform and baseband signal processing for terrestrial CDMA systems, it utilizes simple "bent-pipe" LEO satellite transponders which require no time synchronization and which are uncoordinated with one another. The entire constellation requires 24 satellites for adequate continuity of service over the continental U.S., and with 48 satellites it provides good coverage of all but the polar areas. Rather than trying to connect individual subscribers via the satellite network alone, this less ambitious approach employs a small set of gateway base stations–not more than a half dozen in the U.S. These gateways act very much like cellular base stations, also providing interconnection to the public switched networks. The satellite transponders, on the other hand, appear like independent propagation paths. With multiple satellites in the view of a subscriber and its corresponding gateway, multiple propagation paths are used simultaneously in an intentional version of the unintentional multipath prevalent in terrestrial propagation. As in cellular applications, the CDMA signal structure affords the possibility of optimally combining these multipath components using a RAKE receiver. The gateways will acquire satellites newly appearing above their horizon and begin to uplink pilot and synchronization signals through them. The individual terminal with an omnidirectional antenna will communicate with this new satellite without any knowledge of its position or ephemeris of the satellite. Acquiring new satellites will actually be considerably less demanding than acquiring new multipath components in a terrestrial cellular system, since the duration of the satellite's usefulness will be greater than that of a terrestrial multipath component.

The satellite communication industry seems to be at a technological crossroad. One approach favors tightly coordinated satellite resources, employing on-board-processing, cross-links for proliferated networks, and dedicated user terminals. The other leads to uncoordinated satellites with "bent-pipe" transponders and to user terminals which are extensions of cellular and personal communication terminals, adapted for satellite use only through a different antenna and some RF components.

Relative costs of space segment development and launch obviously favor the latter approach; the question is whether the former offers a significant offsetting advantage. Our personal opinion that it does not is based largely on the following concluding observation.

E. Philosophically Based Conclusion

This observation, which we have recently expanded on elsewhere [7], is that any wireless digital communication system development, whether employing satellite or terrestrial means, cannot afford to ignore the three basic lessons of Shannon's information theory. While the first two, which follow directly from Shannon's celebrated source and channel coding theorems, have become accepted as fundamental to digital communication system design, the third, which applies most particularly to multiple access issues, seems more philosophical in nature and even contrary to accepted engineering principles. Grossly oversimplified, it states that the "best" signal for the "worst" interference will appear as wideband uniform Gaussian noise to the outside observer and that the worst interferer for this best signal will likewise appear as uniform noise. Since interference, whether intentionally hostile or inadvertently disturbing, cannot be avoided, the solution is to employ only wideband noise-like signals. Thus, for any particular user, all interference will appear as wideband noise, against which signal processing digital receivers are most effective. Spectrum spreading CDMA techniques are the embodiment of this philosophy.

Then, most surprisingly, not only does this approach to interference management lead to a simpler and more cost-effective system than through the use of seemingly more precise and elaborate techniques, but ultimately the number of subscribers served and the quality of service provided will be increased as well. It is our belief that this realization will be the accepted norm by the end of the century.

REFERENCES

[1] *Time Magazine* (Jan. 6, 1992) in its choice of the "Man of the Year" and the accompanying cover story makes this case eloquently for a far wider audience than the readership of IEEE TRANSACTIONS.

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CCIR FACT SHEET

Study Group: US 8D   Date: Nov. 13, 1992
Doc. No.: USSG 8D-20   Ref: Question 84-1/8
                                    (Dec. 8/41(Rev.2)

Document Title: MULTI-LAYER INTERFERENCE ANALYSIS AND
                        SIMULATION PROGRAM

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Purpose/Objective:

To introduce a multi-layer interference analysis and simulation program for the development of technical parameters and criteria for frequency sharing between LEO and GSO satellite systems and among multiple LEO RDSS/MSS Satellite Systems operating in the 1-3 GHz band. Use of such a program will assist in developing criteria to enhance sharing and to identify system design and operational factors which can improve the sharing situation.

Abstract:

Due to the technical and operational characteristics of LEO satellite systems, the interference situation between GSO and LEO satellite systems cannot be evaluated fully using conventional techniques of interference analysis. To gain understanding of the multi-layer interference situation and to develop sharing criteria, a multi-layer interference analysis and simulation program was developed. This analysis and simulation program covers interference among five (5) layers of interaction:

Layer 1:   Geometry (orbital dynamics, constellations, etc.)
Layer 2:   Antenna beams, patterns and mutual coupling
Layer 3:   Frequency assignment (beam, channel, time etc.)
Layer 4:   Channel characteristics and link (power, waveform, MA, etc.)
Layer 5:   Traffic/user distribution

Several cases of interference are analyzed and discussed in this paper.

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UNITED STATES OF AMERICA

MULTI-LAYER INTERFERENCE ANALYSIS AND SIMULATION PROGRAM

I. Introduction

WARC-92, in adopting Interim Procedures for the Coordination and Notification of Frequency Assignments of Non-Geostationary-Satellite Networks in Certain Space Services, Resolution COM5/8 (now Resolution 46), invited the CCIR "to study and develop Recommendations on the coordination methods, the necessary orbital data relating to non-geostationary-satellite systems, and the sharing criteria" that would be used to facilitate coordination. This paper discusses the development and use of a multi-layer interference analysis and simulation program which has been developed to evaluate interference between non-geostationary and geostationary satellites and between multiple non-geostationary satellites. In developing this program, the key parameters of the systems required for such an analysis have been identified. The methodology of the program is discussed along with certain sample results. In addition to evaluating interference, this type of analysis can be used to assist in the development of sharing criteria needed to effect coordination of non-geostationary systems.

Since the relative position and pointing of the GSO and LEO satellites constantly change, the parameters affecting interference, both between GSO and LEO satellites, and between LEO satellites, also will change with time and satellite positioning. With these changing parameters, the interference situation cannot be evaluated fully using conventional techniques of interference analysis. To gain understanding of the interference situation and to develop sharing criteria, a multi-layer interference analysis and simulation program was developed. This analysis and simulation program analyzes and simulates interference situation among five (5) layers of interaction:

> Layer 1:   Geometric interaction
> Layer 2:   Antennas interaction
> Layer 3:   Channel Assignment interaction
> Layer 4:   Channel Characteristics interaction
> Layer 5:   Traffic /user distribution

This information paper introduces one of the simulation techniques to analyze the interference situation among various MSS Satellite Systems. Some sample simulation results are also given in this paper as examples.

2. The Five Layer Model of Interference

A systematic approach to partition the complex interference situation among multiple MSS Satellite Systems (both GSO and non-GSO) is to develop a multi-layer interference model such that computer analysis and simulation program can be developed around each layer. Initially, five major layers of the interference situation have been identified and computer simulation programs have been developed around these five layers.

2.1 Layer 1: Geometric Layer

Since the relative position and pointing of GSO and LEO satellites constantly change, it is necessary to develop some common reference systems for all satellite systems such that all satellites and user terminals can have a specific coordinate with respect to the same reference point. In this layer, the center of the earth has been identified as the center of this reference system. Each interference source (i.e., a transmitter) and victim (i.e., a receiver) is identified by its own coordinate with respect to the center of the Earth. The Z-axis of any point is defined as the vector from this particular point to the center of the earth. The X-axis is defined as the same of the velocity vector of this point. Figure 1 illustrates this geometric layer and the reference system.

The main purpose of this geometric layer is to determine whether any pair of interference source and interference victim has the line-of-sight relation. It is assumed in this simulation program that there is interference when a source and a victim are in direct line-of-sight. Scattering reflection and refraction effects are considered secondary effects and are not included in the program at this stage. These secondary effects can be incorporated into the program if models of these effects be developed.

Major parameters to be input into this geometric layer include:

- satellite altitude
- inclination angle
- orbit phasing
- orbit location or sub-satellite point (for GSO)
- orbit eccentricity
- apogee and perigee
- others

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The computer program would simulate orbits and constellations of different GSO or non-GSO systems, calculate the relative positions of each points (either an interference source or victim) and determine whether two points (i.e. source and victim) are in line-of-sight or being blocked by earth, at any time of the simulation period.

2.2 Layer 2: Antenna Layer

Once the line-of-sight between the interference source and interference victim is established, the interaction between the source antenna and the victim antenna has to be modeled. Figure 2 illustrates the interaction among a single interference source and multiple interference victims.

An interference source can transmit interference through the mainbeam, sidebeams or backlobes of its transmit antenna and an interference victim can receive interference through the mainbeam, sidelobes or backlobes of its receive antenna.

To analyze the interference situation, the actual measured antenna patterns, including both main beam and sidelobes, or computer simulated patterns can be located at any point of the coordinate to simulate the transmit or receive antenna. The relative distance and spatial loss between the source and victim can be calculated by Layer 1 programs. Thus the relative gain between the source and victim along the line-of-sight direction can be determined.

Another factor affecting the relative gain between the source and the victim is the polarization isolation between the source and the victim. The computer program examine the orientation of the source and victim antennas, the relative polarization isolation and the resulting relative gain between the source and the victim.

2.3 Layer 3: Channel Assignment

After the relative gain(s) between the interference source and the interference victim(s) have been established by the computer programs in Layer 2, Layer 3 represents the time, frequency and beam assignments at each points. Figure 3 shows an example of the Channel Assignments (time, frequency and beam) of a sample point (either a source or a victim).

Different MSS systems have their own unique frequency plan, channelization plan, frequency re-use plan and beam hopping plan. All these have been modeled and incorporated into Layer 3 programs.

2.4 Layer 4: Channel Characteristics

Layer 4 is in fact a sub-layer of Layer 3, which describes the detailed characteristics of the channel modeled in Layer 3. These channel characteristics include:

- modulation wave form e.g. (Sin X/X)^2 or others
- signal filtering
- power or power spectral density (PSD)
- frame structure (for TDMA)
- spectral spreading (for CDMA)

As an example, Figure 4 illustrates the channel characteristics of three different channels (FDMA, TDMA and CDMA).

2.5 Layer 5: Traffic and User Distribution

The traffic distribution of a MSS satellite is highly local time dependent. During the busiest hours (e.g., 9 to 11 a.m. or 5 to 7 p.m.) the satellite could be fully loaded. In the late evening or early morning, the satellite could be only used lightly. Figure 5a is a typical traffic distribution over a 24-hour period of local time. The traffic distribution of each satellite affects the interference generated by this satellite at a specific time of the day. For simplicity, similar traffic distribution profiles are used for MSS satellites. The total number of channels carried by each MSS satellite can be adjusted as an input to the program of this Layer.

Modeling of the user distribution is much more difficult. Two models of user distribution are identified to simplify this problem: Uniform Distribution Model and Non-overlapped Distribution.

In the uniform distribution model, it is assumed that users of different MSS systems are distributed evenly and uniformly over the same geographic area (Figure 5b). In the non-overlapped distribution, it is assumed that users of different MSS systems are located in different geographic areas (Figure 5c).

Combining the traffic distribution profile of a MSS satellite and the user distribution, interference between users and satellites, and between satellite and satellite can be simulated for a long period of time. However, to reduce the complexity of the problem, user-to-user interference is not considered in this Layer.

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3. Assumptions and Outputs

Many assumptions were made to reduce the complexity of the simulation, for example:

- If actual antenna pattern is not available, equivalent, simulated antenna gain pattern is used for certain antenna apertures.

- It is assumed that a TDMA MSS systems is fully synchronized within itself and a simple time-average factor can be used to estimate the interference generated by the burst type of transmission.

- It is assumed that there is no correlation and synchronization between different MSS systems, whether they are TDMA, FDMA or CDMA.

- The power spectral density (PSD) is "measured" at the output port of the receiving antenna of the victim.

The main output of this multi-layer simulation program is the Power Spectral Density (PSD) generated by various sources of interference at any given victim location and at any time of the day. To visualize this output, one can imagine that a spectrum analyzer is used at a specific victim location to estimate the interference power spectral density over a certain period of time. Sweeping the spectrum analyzer over a large band provides an overall estimate of the interference situation and sweeping over a finely quantitized band provides a more accurate estimate of the interference power.

To make the program output more comprehensive, several data reduction programs and statistic programs were developed to analyze the outputs. Figure 6 is an example of a typical output of this simulation program and Figure 7 is the statistical summary of a specific interference situation. Figure 6 shows the spectral power density at two frequencies, of the sum of all interference from various sources, over a three hour orbit at a specific LEO satellite. Figure 7 provides the statistical summary of Figure 6, which shows over 65% of time, the psd of interference at this specific point of the constellation, the interference level would be over -227 dBw/4 kHz. Figure 6 and Figure 7 only provide a simulation for three hour orbit time. If longer orbit time is simulated, then more realistic estimation of the interference interaction can be studied.

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Once the power spectral density of the interference is established, individual MSS systems can use this interference PSD to estimate the aggregate Io and the impact on its own Eb/(No+Io). This aggregate PSD can also be used as a measure to allocate expected interference noise from different MSS systems, and thus can become one of the criteria to be used for frequency sharing among different MSS systems.
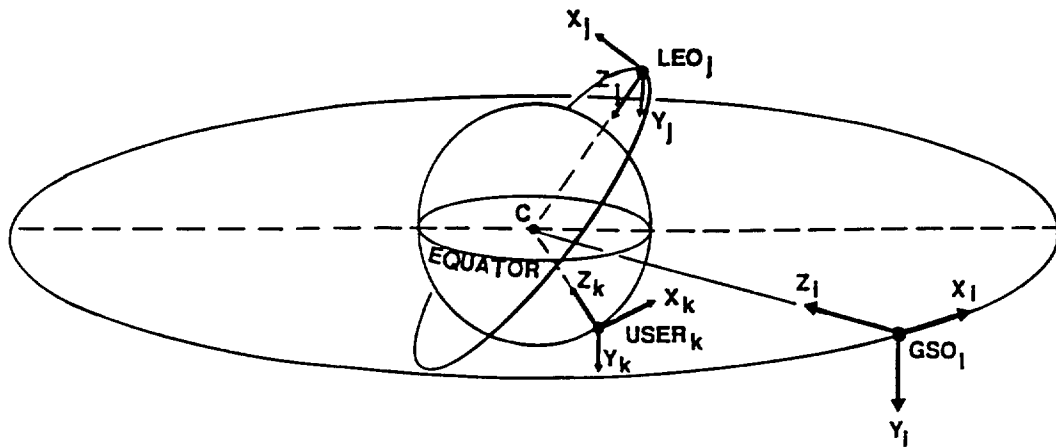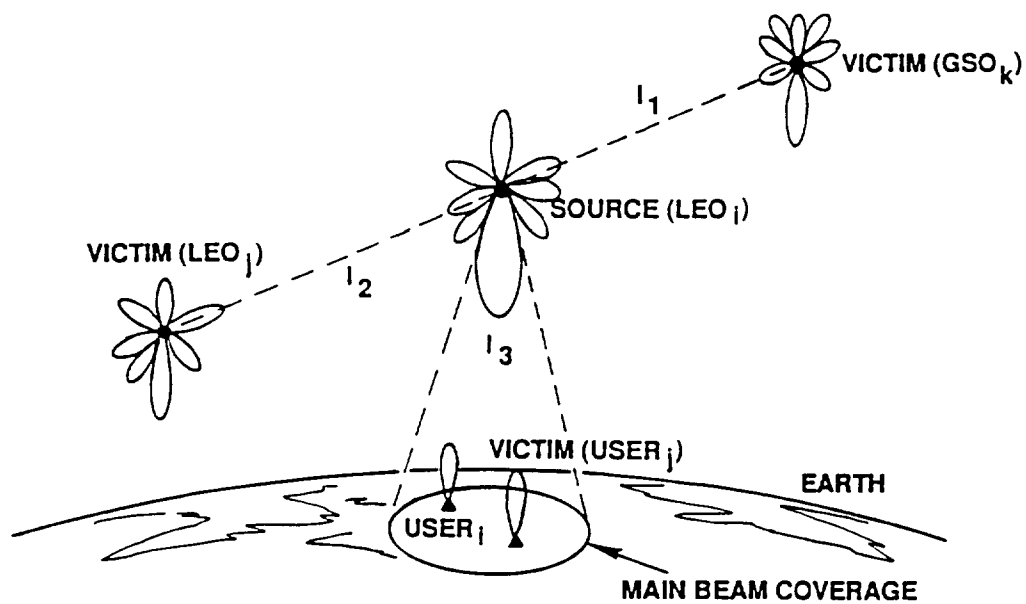
Figure 1 - Co-ordinate System of the Geometric Layer

Figure 2 - Example of Antenna Interaction